

# Quantum ballistic transport in in-plane-gate transistors showing onset of a novel ferromagnetic phase transition\*

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## Abstract

We study one-dimensional transport in focused-ion-beam written in-plane-gate transistors on III-V heterostructures at moderately low temperatures at *zero* bias *without any* external magnetic field applied. In accordance with a recent proposal of A. GOLD and L. CALMELS, *Valley- and spin-occupancy instability in the quasi-one-dimensional electron gas*, Phil. Mag. Lett. **74**, 33-42 (1996) and earlier experimental data, we observe plateaux in the source-drain conductivity considered as a function of the gate voltage, not only at multiples of  $2e^2/h$  but also clearly at  $e^2/h$ , just before the channel closes to zero conductivity. This may be interpreted as a many-electron effect, namely as a novel ballistic ferromagnetic ground state evading standard descriptions and theorems.

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# 1 Introduction

In 1988 the quantization of the conductivity in one-dimensional short channels was discovered [1]. Here we focus on the conductivity of the lowest one-dimensional subbands, namely for an occupancy of one or two of them. We find that the quantum of conductivity is *not*  $2e^2/h$  but simply  $e^2/h$ . Our measurements are performed in  $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ -heterostructure in-plane-gate (IPG) transistors operated at moderately low temperatures ( $1 - 2\text{ K}$ ) with *zero bias* and *zero external magnetic field*.

We interpret our findings as a lifting of a spin occupancy degeneracy within the spirit of a recent proposal by GOLD and CAMELS [2] who claim that in one dimensional quantum wires at low electron densities there might exist a valley occupancy instability (in multivalley semiconductors like Si) or rather a spin occupancy density (even in direct semiconductors like GaAs).

The response to an applied finite external magnetic field discloses the intricate nature of the new state which seems to be a realization of (longitudinally) polarized electron transport [3], the polarization being of spontaneous nature here. In fact, from a theoretical point of view it may be regarded as some sort of ferromagnetic ground state evading the standard spin model (HEISENBERG) picture (and hence the associated low-dimensional no-go-theorems) [4] rather being reminiscent of the itinerant (BLOCH) picture [5] without being identical to the latter. In fact, in some sense the observed state bears some resemblance to the notion of a chiral (say gapless handed) fermion state stabilizing under a finite  $\mathbf{E} \cdot \mathbf{B}$ .

In what follows we explain the principles of IPG devices, report the experimental data, and give an outline of the theoretical perspective.

## 2 IPG design and operation

The principle of focused-ion-beam (FIB) implantation and the FIB-written in-plane-gate (IPG) transistor are explained in Figures 1-3.

1. By direct implantation of an FIB line of approximately 50 nm width we insulate two areas of the two-dimensional (2D) electron gas against each other, that is, there does

not flow any current (I) up to a voltage (U) of some volts.

2. By implantation of a somewhere disconnected FIB line there will flow some current through the resulting narrow gap, forming a point contact. The latter can be considered as a limit of a quasi-one-dimensional (quasi-1D) current carrying channel.
3. By implanting two FIB lines we form three regions defining a ‘T’-shaped pattern leaving open a narrow gap at its vertex. In this way source and drain regions are created. Current flowing from source to drain can be controlled by applying a voltage to the third region, the gate. Thus we have a one-dimensional channel controlled by a lateral field effect: the IPG transistor [7].

Note that the IPG transistor is an all-purpose device in the sense that it works in the classical limit at room temperature as well as in the quantum regime at low temperatures. In particular, our samples fabricated using IPG technique are rugged enough to exhibit a very long lifetime, as compared, for example, with more common SCHOTTKY gate devices. At room temperature the IPG transistor does work much like an ordinary junction field effect transistor (JFET). In this work, however, we study only the zero-bias (quantum) resistivity of the source-drain channel at moderately low temperatures ( $1 - 2$  K).

### 3 Experiments

We grow a GaAs/Al<sub>0.33</sub>Ga<sub>0.67</sub>As modulation doped heterostructure by molecular beam epitaxy on a semi-insulating GaAs (100) substrate. It consists of a 2  $\mu$ m nominally doped GaAs buffer layer and a 23 nm undoped Al<sub>0.33</sub>Ga<sub>0.67</sub>As spacer layer, followed by 50 nm of Si-doped Al<sub>0.33</sub>Ga<sub>0.67</sub>As and a 10 nm GaAs cap. The two-dimensional electron gas is localized in a sheet within the GaAs buffer right at the interface to the spacer. The measured values for the electron sheet density and the electron mobility are

- at room temperature  $4.7 \times 10^{11} \text{ cm}^{-2}$  and  $6\,638 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ ,
- at  $T = 77 \text{ K}$  in the dark  $3.6 \times 10^{11} \text{ cm}^{-2}$  and  $166\,900 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ ,
- at  $T = 5 \text{ K}$  in the dark  $3.1 \times 10^{11} \text{ cm}^{-2}$  and  $666\,000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ ,

respectively. By “in the dark” we indicate that we measure all values without illumination prior to or during the HALL experiment.

After the growth process the sample is mesa-etched into a standard HALL-bar geometry with a width of  $150\mu\text{m}$  and a distance of  $200\mu\text{m}$  between ohmic contacts which were made with an AuGe/Ni alloy. Using an focused-ion beam (FIB) of 100 keV Ga<sup>+</sup> ions, nominally 50 nm wide insulating lines were directly written at normal incidence with a dose of  $1 \times 10^{12} \text{ cm}^{-2}$  to define in-plane gated channels of  $1\mu\text{m}$  width. No subsequent annealing has been applied to the FIB-written line.

Transport measurements are performed at  $T = 1 - 2\text{K}$  in the dark with zero source-drain bias without magnetic field applied. In addition, the sample can be mounted in two different orientations with respect to an external magnetic field, such that the latter can be applied perpendicularly to the samples surface or else in direction parallel to the conducting channel. We measure the a.c. voltage drop between source and drain in injecting an 1 nA alternating c.w. current with constant r.m.s. value. The chosen frequency is 81 Hz and voltage detection is performed with a standard lock-in setup including an ITHACO DYNATRAC 391A lock-in amplifier supplemented by a HEWLETT-PACKARD 4142B parameter analyzer. All measurements are done by first sweeping the gate voltage down to negative values and then sweeping up again. This always results in double traces in the figures, showing the reproducibility of the data.

## 4 Data analysis

At zero bias the measured nominal source-drain voltage  $V_{sd}$  divided by the constant injection current  $I_{sd}$  equals the sum  $R$  of the resistance  $R_{true}$  of the constriction (which is of interest here) and the series resistance  $R_s$  built of the areas between the contacts. The latter has to be subtracted in order to get the correct values from which we can read off the quantized values. Unfortunately we do not know its exact value. Denoting the  $i$ -th trial subtraction resistance by  $R_i$  we obtain a family ( $i = 1, 2, \dots$ ) of conductivity curves of the form

$$\sigma_i(V_g) = \frac{1}{R_{true}(V_g) + R_s - R_i}, \quad (1)$$

from which we pick off the one which has the best overall linear rising behaviour with increasing gate voltage  $V_g$ . For further details concerning the resistance  $R_s$  of the triangular-shaped entrance and outlet of the channel the reader is referred to Ref. [7].

Figures 4 and 5 show data taken during different sessions from measurements without an external magnetic field applied. The curves with the overall negative slope show the resistivities versus the gate voltage, the curves with the overall positive slope show the conductivities versus the gate voltage, respectively. The observed conductivity structure is independent of sweep direction, i.e. there are no single-shot artifacts. There is not only a quantization step close to  $2e^2/h$ , but also a clear plateau at  $e^2/h$  even though there is no magnetic field applied at all. The next quantization occurs at  $4e^2/h$  which is consistent with theory, predicting the effect at  $3e^2/h$  to be absent [2]. The structure at  $e^2/h$  can be observed in all samples we prepare. However, it is not always as pronounced. Figures 6-9 show analogous curves in case of a perpendicular and longitudinal external magnetic field. A magnetic field perpendicular to the sample's surface suppresses the effect whereas a magnetic field parallel to the direction of transport at least does not have any influence on its appearance.

## 5 Conclusion

By using focused ion beams we define small structures within the plane of a two-dimensional electron gas. In particular, by controlling a quasi-1D channel its electrical width is squeezed down to the quantum wire regime. Though one must admit that ion beam damage adversely influences the electron mobility in the channel it is expected that quantization effects can be seen most clearly at the point just before the channel closes. In fact, this is what has been observed.

Our main finding is a conductivity quantization step at  $e^2/h$  in an in-plane-gate transistor operated at moderately low temperatures ( $1 - 2$  K) with *zero bias* and *zero external magnetic field*. Some indications of this effect may be extracted from the data in the work by DE VRIES *et al.* [8]. The analogous effect was not seen in recent high-precision experiments by THOMAS *et al.* using split gate devices [9]. However, the evolution of half plateaus

as a function of an additional d.c. electric field (and perpendicular external magnetic field) in a ballistic quasi-1D constriction have been found by PATEL *et al.* [10]. Evidently, in-plane-gate devices differ from split-gate-devices in one essential aspect, namely in the geometrical form of the lateral band structure, for which we have no general theory so far. We have to take into account that the physical situation in our devices is not exactly equivalent to the one in split-gate setups. Deviations from the exact quantization rule are most probably due to ionized impurity scattering in the sample [11]. However, there is definitely an additional structure giving us notice of new physics in ballistic electron transport.

We interpret our findings at *zero bias* and *zero external magnetic field* as a true many-body effect in a one-dimensional electron system. More speculatively, it may be a form of a novel ferromagnetical ordered state which we christened “ferromagnetism on the wing”. The calculations of GOLD and CAMELS [2] suggest the existence of a spin instability at low electron density in a GaAs quantum wire. This mechanism should manifest itself in exactly the same way as shown up in our experiment. Consequently, it fits well into the framework of spin-polarized transport [3], the polarization here being due to an electron-electron correlation. This explanation is adjacent because of the apparently spontaneous nature of the state and its response to the external conditions which seems to favour a stability under a finite  $\mathbf{E} \cdot \mathbf{B}$ . Future studies should elaborate on this fact.

## 6 Acknowledgements

One of us (A.D.W.) would like to thank A. GOLD for sending him a preprint of his paper. For R.D.T. it is a great pleasure to thank (a) A. FISCHER for introducing him to the secrets of MBE growth and (b) D. DE VRIES for giving him some lessons on the FIB/IPG stuff during his stay at the Max-Planck-Institut für Festkörperforschung, Stuttgart, in 1995. Finally he is also very grateful to R.L. STULLER, H. HESSLING, and Professor N. SCHOPOHL for inspiring discussions.

## 7 References

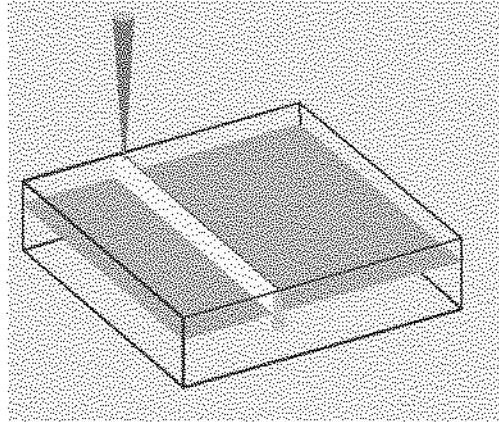
- [1] B.J. VAN WEES, H. VAN HOUTEN, C.W.J. BEENAKKER, J.G. WILLIAMSON, L.P. KOUWENHOVEN, D. VAN DER MAREL, and C.T. FOXON, *Quantized conductance of point contacts in two-dimensional electron gas*, Phys. Rev. Lett. **60**, 848-850 (1988);  
D.A. WHARAM, T.J. THORNTON, R. NEWBURY, M. PEPPER, H. AHMED, J.E.F. FROST, D.G. HASKO, D.C. PEACOCK, D.A. RICHIE, and G.A.C. JONES, *One-dimensional transport and the quantisation of the ballistic resistance*, J. Phys. **C21**, L209-L214 (1988);  
D.A. WHARAM, M. PEPPER, H. AHMED, J.E.F. FROST, D.G. HASKO, D.C. PEACOCK, D.A. RICHIE, and G.A.C. JONES, *Addition of the one-dimensional quantised ballistic resistance*, J. Phys. **C21**, L887-L891 (1988);  
D.A. WHARAM, R. NEWBURY, M. PEPPER, D.G. HASKO, H. AHMED, J.E.F. FROST, D.A. RICHIE, D.C. PEACOCK, G.A.C. JONES, T.J. THORNTON, and U. EKENBERG, *Ballistic electron transport in quasi-one-dimensional systems*, Surf. Sci. **229**, 233-238 (1990).
- [2] A. GOLD and L. CALMELS, *Valley- and spin-occupancy instability in the quasi-one-dimensional electron gas*, Phil. Mag. Lett. **74**, 33-42 (1996).
- [3] G.A. PRINZ, *Spin-polarized transport*, Physics Today **4/95**, 58-63 (1995).
- [4] W. HEISENBERG, *Zur Theorie des Ferromagnetismus*, Z. Phys. **49**, 619-636 (1928);  
N.D. MERMIN and H. WAGNER, *Absence of ferromagnetism or antiferromagnetism in one- or two-dimensional isotropic Heisenberg models*, Phys. Rev. Lett. **17**, 1133-1136 (1966).
- [5] F. BLOCH, *Bemerkung zur Elektronentheorie des Ferromagnetismus und der elektrischen Leitfähigkeit*, Z. Phys. **57**, 545-555 (1929);  
C. HERRING, *Exchange interactions among itinerant electrons in Magnetism Vol. IV*, ed. by G.T. RADO AND H. SUHL, Academic Press, New York and London, 1966;  
D.C. MATTIS (ed.), *The many body problem*, World Scientific, Singapore, 1993.



- [6] A.D. WIECK and K. PLOOG, *In-plane-gate quantum wire transistor fabricated with directly written focused ion beams*, Appl. Phys. Lett. **56**, 928-930 (1990);  
A.D. WIECK and K. PLOOG, *High transconductance in-plane-gated transistors*, Appl. Phys. Lett. **61**, 1048-1050 (1992).
- [7] D.K. DE VRIES and A.D. WIECK, *Series resistance of in-plane-gated transistors and quantum point contacts*, J. Vac. Sci. Technol. **B13**, 394-395 (1995).
- [8] D.K. DE VRIES, K. PLOOG, and A.D. WIECK, *Quasi-one-dimensional ballistic electron transport in in-plane-gate channels at liquid-nitrogen temperature*, Solid State Electronics **37**, 701-703 (1994).
- [9] K.J. THOMAS, M.Y. SIMMONS, J.T. NICHOLLS, D.R. MACE, M. PEPPER, and D.A. RITCHIE, *Ballistic transport in one-dimensional constrictions formed in deep two-dimensional electron gases*, Appl. Phys. Lett. **67**, 109-111 (1995).
- [10] N.K. PATEL, L. MARTÍN-MORENO, M. PEPPER, R. NEWBURY, J.E.F. FROST, D.A. RITCHIE, G.A.C. JONES, J.T.M.B. JANSSEN, J. SINGLETON, and J.A.A.J. PERENBOOM, *Ballistic transport in one dimension: additional quantisation produced by an electric field*, J. Phys. **C2**, 7247-7254 (1990);  
N.K. PATEL, J.T. NICHOLLS, L. MARTÍN-MORENO, M. PEPPER, J.E.F. FROST, D.A. RITCHIE, and G.A.C. JONES, *Evolution of half plateaus as a function of electric field in a ballistic quasi-one-dimensional constriction*, Phys. Rev. **B44**, 13549-13555 (1991).
- [11] G. TIMP, *When does a wire become an electron waveguide?* Semiconductors and Semimetals **35**, 113-190 (1992);  
E.G. HAANAPPEL and D. VAN DER MAREL, *Conductance oscillations in two-dimensional Sharvin point contacts*, Phys. Rev. **B39**, 5484-5487 (1989);  
D. VAN DER MAREL and E.G. HAANAPPEL, *Model calculations of the quantum ballistic transport in two-dimensional constriction-type microstructures*, Phys. Rev. **B39**, 7811-7820 (1989);

C.S. CHU and R.S. SORBELLO, *Effects of impurities on the quantized conductance of narrow channels*, Phys. Rev. **B40**, 5941-5949 (1989).

## 8 Figures



insulation through p-type focused ion beam (FIB) implantation

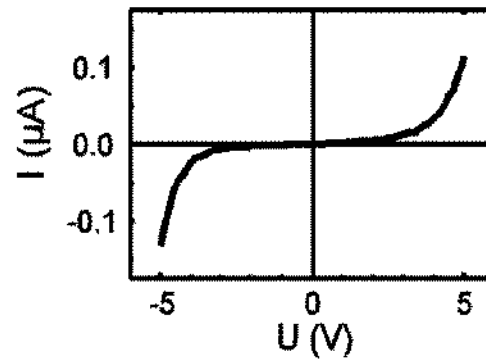
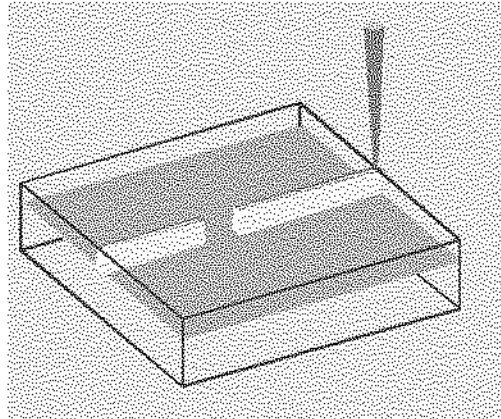


Figure 1: Evolution of insulating lines in a two-dimensional electron gas to an in-plane-gate (IPG) transistor (Part 1 of 3).



forming of a channel by means of  
a FIB written disconnected path

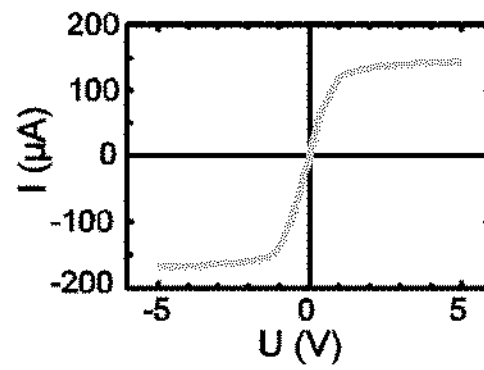
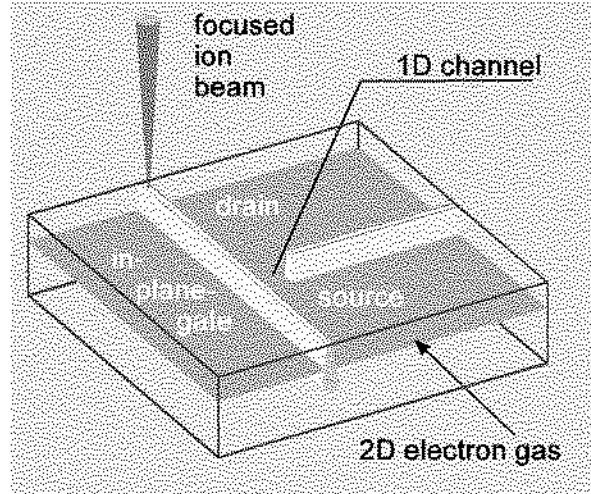


Figure 2: Evolution of insulating lines in a two-dimensional electron gas to an in-plane-gate (IPG) transistor (Part 2 of 3).



by forming an in-plane gate we control electron transport through the channel

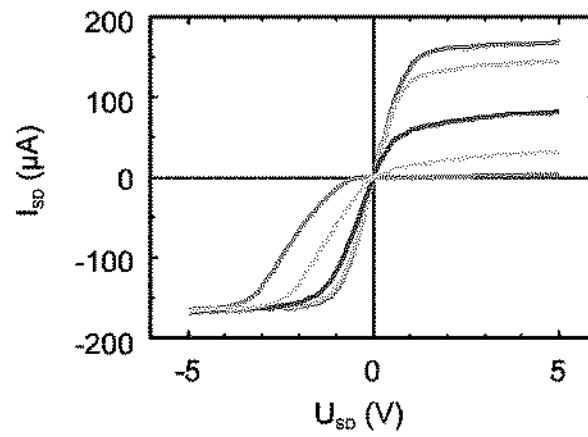


Figure 3: Evolution of insulating lines in a two-dimensional electron gas to an in-plane-gate (IPG) transistor (Part 3 of 3).

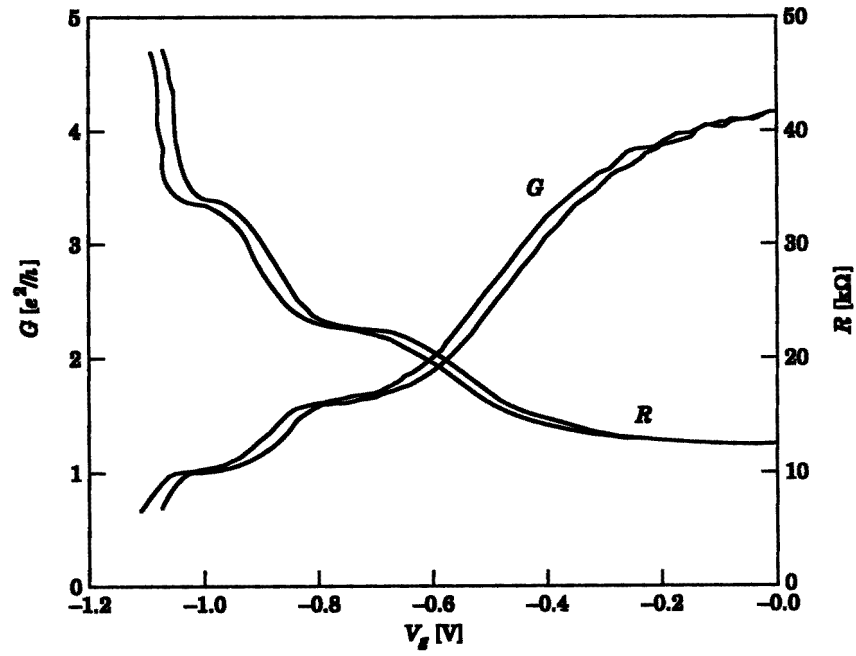


Figure 4: Zero-bias conductivity  $G$  (in units of  $e^2/h$ ) and resistance  $R$  (in  $k\Omega$ ) of an IPG transistor at low temperatures  $T = 1.5$  K versus the IPG voltage  $V_g$  (in V) at  $B = 0$ .

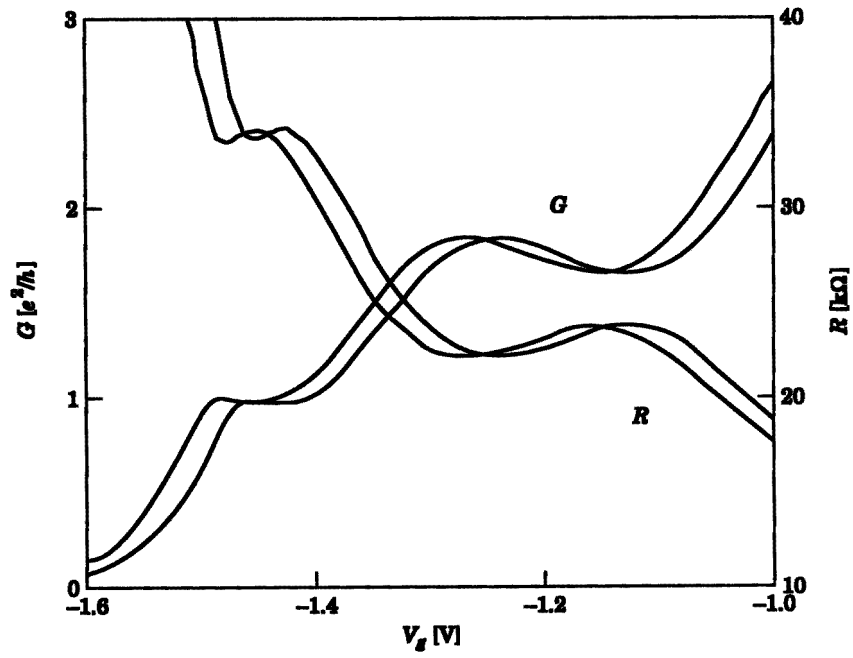


Figure 5: Same as Fig. 4, but with different scaling factors. These data are taken during a later measurement.

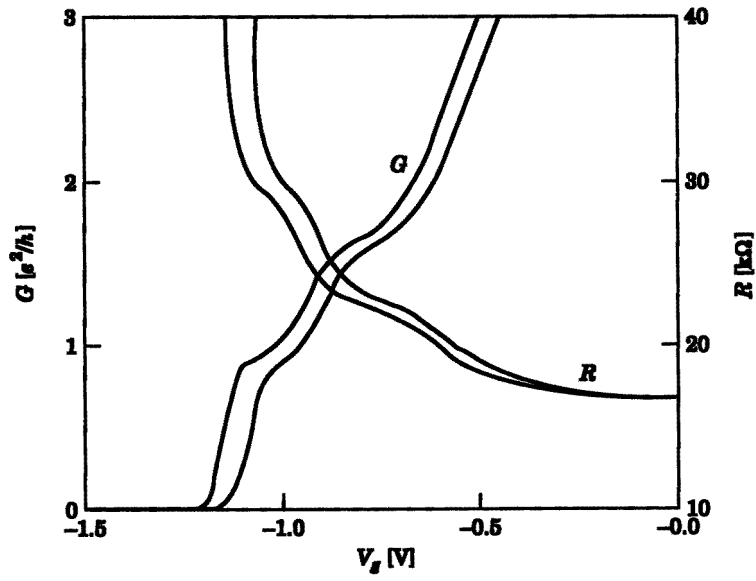


Figure 6: Same as Fig. 4 and 5. Note that for gate voltages  $V_g < -1.2$  V the resistance increases monotonically, i.e. there is no conductivity plateau below  $e^2/h$ .



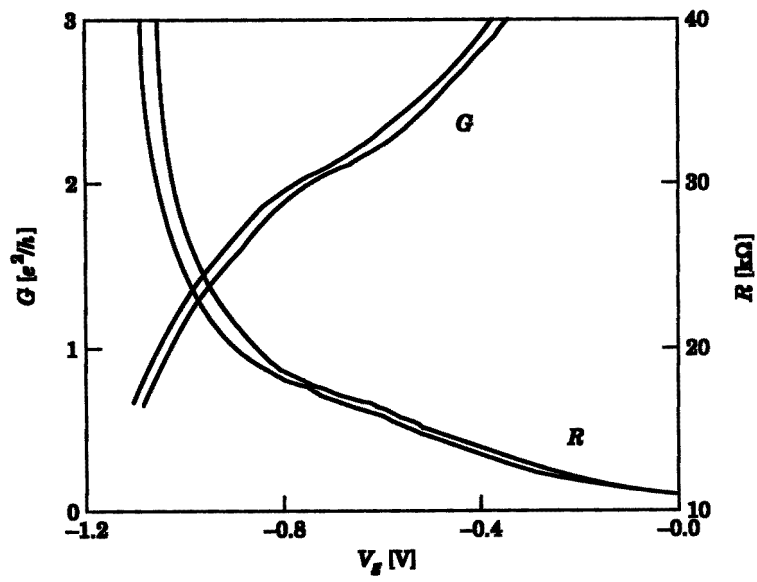


Figure 7: The same measurement as in Fig. 6, but with a magnetic field applied perpendicular to the sample's surface, giving a finite  $\mathbf{E} \times \mathbf{B}$  value. Quantizations are suppressed.

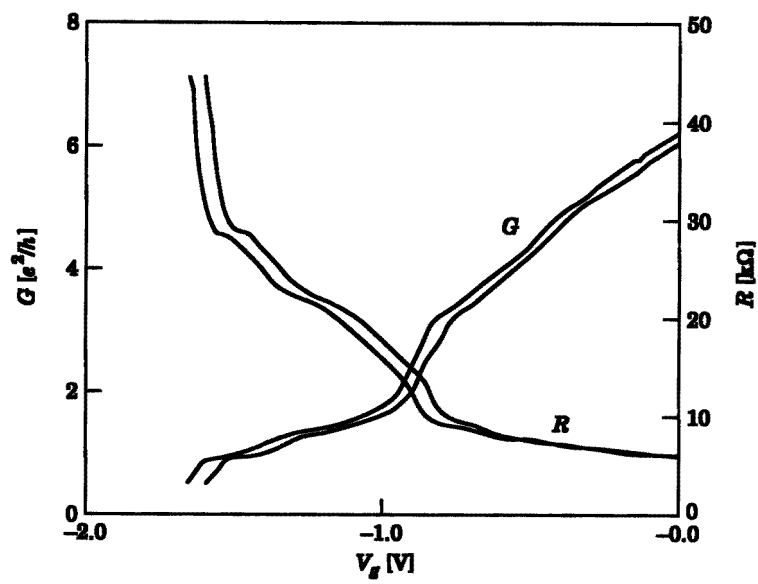


Figure 8: Same measurement as in Figs. 6-7 without a magnetic field.

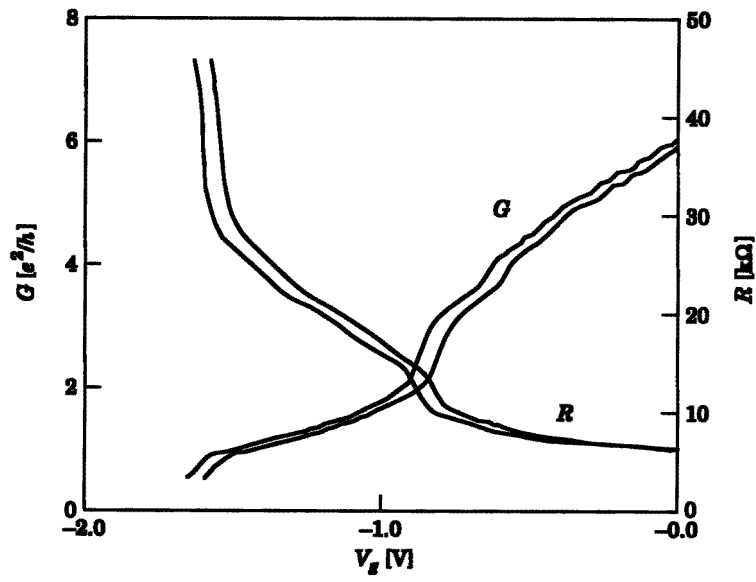


Figure 9: Same measurement as in Fig. 6-7, but with  $B = 3$  T, applied in transport direction of the 1D channel giving a finite  $\mathbf{E} \cdot \mathbf{B}$  value. All ballistic features are conserved.